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Space heating with ultra-low-temperature district heating – a case study of four single-family houses from the 1980s

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Abstract

District heating is predicted to play a large role in the future fossil free energy system. Apart from providing energy savings by utilizing surplus heat, the district heating system also provides flexibility to fluctuating electricity generation by bridging the electricity and the heating sector. These benefits can be maximized if district heating temperatures are lowered as much as possible. In this paper we report on a project where 18 Danish single-family houses from the 1980s were supplied by ultra-low-temperature district heating with a supply temperature as low as 45 °C for the main part of the year. The houses were heated by the existing hydraulic radiator systems, while domestic hot water was prepared by use of district heating and electric boosting. This paper evaluated the heating system temperatures that were necessary in order to maintain thermal comfort in four of the houses. First the four houses were modelled in the building simulation tool IDA ICE. The simulation models included the actual radiator sizes and the models were used to simulate the expected thermal comfort in the houses and resulting district heating return temperatures. Secondly measurements of the actual district heating return temperatures in the houses were analysed for different times of the year. The study found that existing Danish single-family houses from the 1980s can be heated with supply temperatures as low as 45 °C for the main part of the year. Both simulation models and test measurements showed that there is a large potential to lower the district heating temperatures.

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Keywords: Ultra-low-temperature district heating; radiator; IDA ICE; heating power; heat demand

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1. Introduction

District heating (DH) covers approximately 13% of the heat demand in the EU at the current state. This share is expected to increase in the future, as expansion of the DH networks has been found to be an economically beneficial tool in the transition to a low-CO2 energy system [1]. The efficiency of the new DH systems can be increased significantly, if they are operated with low supply and return temperatures, according to the principles of 4th Generation District Heating [2]. A reduction of the DH temperature has two positive effects on the energy efficiency of the heat supply. Firstly, when the DH temperatures are reduced, the heat losses from the pipe networks are also reduced. This can generate significant energy savings, as the reductions in heat loss can be estimated to 30 % when supply and return temperatures are reduced from 80 °C/40 °C to 60 °C/30 °C. Secondly the efficiency of the heat production is increased for heat sources such as geothermal heat, heat pumps or solar heating. The efficiency of the heat production is estimated to increase by approximately 10 % in solar thermal plants and 30 % in heat plants supplied by heat pumps, if supply and return temperatures are lowered from 80 °C/40 °C to 60 °C/30 °C. Additionally the heat production efficiency is increased when return temperatures are lowered in heat plants with flue gas condensation supplied by natural gas or wet biomass. Consequently a reduction in the DH temperatures can amount to significant total energy savings.

Danish DH is characterized by a large outspread, and relatively low supply and return temperatures. However recent research has shown that there is further potential to lower the DH temperatures. Currently, approximately 47 % of the total Danish heat demand is covered by DH [3]. Even low-density areas are at times supplied by DH, for example approximately 40 % of the Danish single family houses are heated by DH [4]. Current supply and return temperatures are as low as 70/40 on average [5]. Nevertheless a large effort is currently taking place to reduce the temperatures further. This is done by the DH companies, through installation of automatic temperature optimization software [6] or through research projects that investigate the opportunity to lower the DH supply temperatures to 55 °C or 60 °C in both new and existing buildings [7].

The temperature reductions in the DH networks are limited by the demands and technical requirements in the buildings. In houses or commercial buildings these limitations are generally set by either the domestic hot water (DHW) requirements or the design of the space heating installations. The supply temperature in current Danish DH networks is generally limited by the DHW systems, which are typically designed for preparation of hot water at a temperature above 60 °C. When DHW is stored at this temperature, the risk of Legionnaires' disease is reduced, as the Legionella bacteria mainly grow at lower temperatures. If DH temperatures go below 55 °C, the DHW must be prepared through for example an instantaneous heat exchanger, to avoid Legionella growth in the DHW [8]. By use of the direct heat exchanger, or other solutions as described by Yang, Li & Svendsen in [9], the DH supply temperature can be lowered to around 50 °C, which is enough to deliver DHW at the required comfort temperature of 40-45 °C. This type of DH is commonly referred to as low-temperature district heating (LTDH).

The DH temperatures can be lowered further if the DHW is heated through a combination of DH and electricity. This is also referred to as ultra-low-temperature district heating (ULTDH). DH is used to heat the domestic hot water to a temperature of e.g. 35 °C and the temperature is then further raised to 40-45 °C by for example a micro heat pump [10] or an instantaneous electric heater. In this case the space heating systems are the limiting factor with regards to temperature reductions. For example it may not be possible to lower the supply temperature to 40 °C in old buildings where the heat loss is large and the heating elements are small. However recent research has shown that many existing buildings can be heated by low-temperature heating without problems. This is partly due to the fact that the supply temperature in a LTDH system can be increased in peak periods during cold winter times when the space heating requirements are higher. Ultimately the lower limit for the DH supply temperature could be as low as 30 °C in new buildings with floor heating. Fig. 1 summarizes the different types of DH based on the technical limitations and in correspondence with earlier definitions as described in [2,6,11].

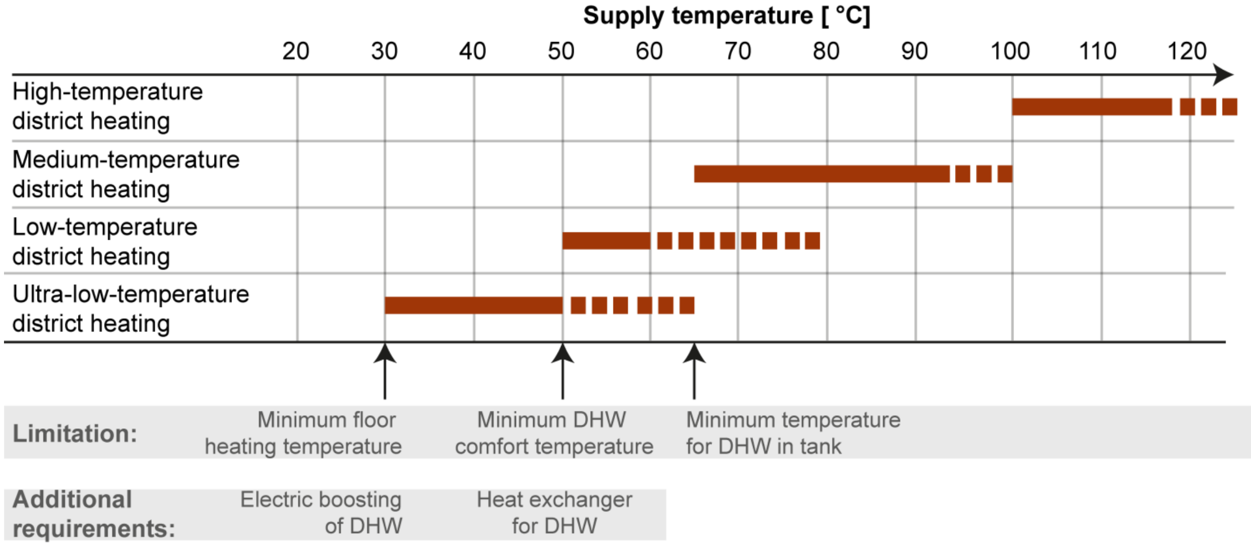

Fig. 1.Definition of four different types of district heating where temperatures are limited by the technical requirements of the buildings.

Since the space heating system is the limiting factor in ULTDH-systems, it is crucial to investigate the design of the space heating systems, when an existing building area is to be supplied by ULTDH. Most Danish houses are heated by hydraulic radiators that are designed for supply and return temperatures such as 90 °C/70 °C or 70 °C/40 °C. However even in these houses it is reasonable to expect that the typical space heating demands can be covered with low-temperature heating, since radiators are designed for extreme conditions with very cold outdoor temperatures. This was verified in our recent investigation of heating power and heating demands in typical Danish single-family houses from the 1900s [12]. Furthermore it is illustrated in several Danish pilot projects where the use of ULTDH in existing building areas has been successfully tested [6,10,11]. Nevertheless none of these projects investigated the limitations of the space heating systems in detail. This study therefore set out to perform a detailed analysis of the space heating systems in four Danish single-family houses heated by ULTDH.

1.1. Aim of study

This study aimed to investigate how far we can lower the heating system temperatures in existing Danish single-family houses without compromising thermal comfort. The study was carried out through measurements from a real test case where four houses where supplied by ULTDH. Since the actual heating system operation can be affected by technical malfunctions or occupant behaviour, the measurements were compared to results from dynamic simulation models, which were used to evaluate the ideal heating system temperatures and the thermal comfort in the houses.

2. Description of case houses

The investigations were carried out as a case study of four single-family houses built around 1980. The houses are illustrated in Fig. 2. All of the houses have 2-3 occupants and a heated floor area of around 150 m2. House 1 and 2 furthermore holds an unheated basement. All building elements in the houses were well insulated at the time of construction, and due to the young age, the only renovations carried out is replacement of windows in some houses. The constructions of the houses are described in Table 1, together with the estimated U-values of each construction element. Linear heat losses are based on internal measures and assumed to be 0.07 W/mK around windows, 0.15 W/mK at foundations and exterior wall joints, and 0.12 W/mK for connections between roof and exterior walls. Both constructions and U-values correspond to the standard for this type of houses as given by the Danish Building Research Institute [13] and the Danish Energy Agency [14].

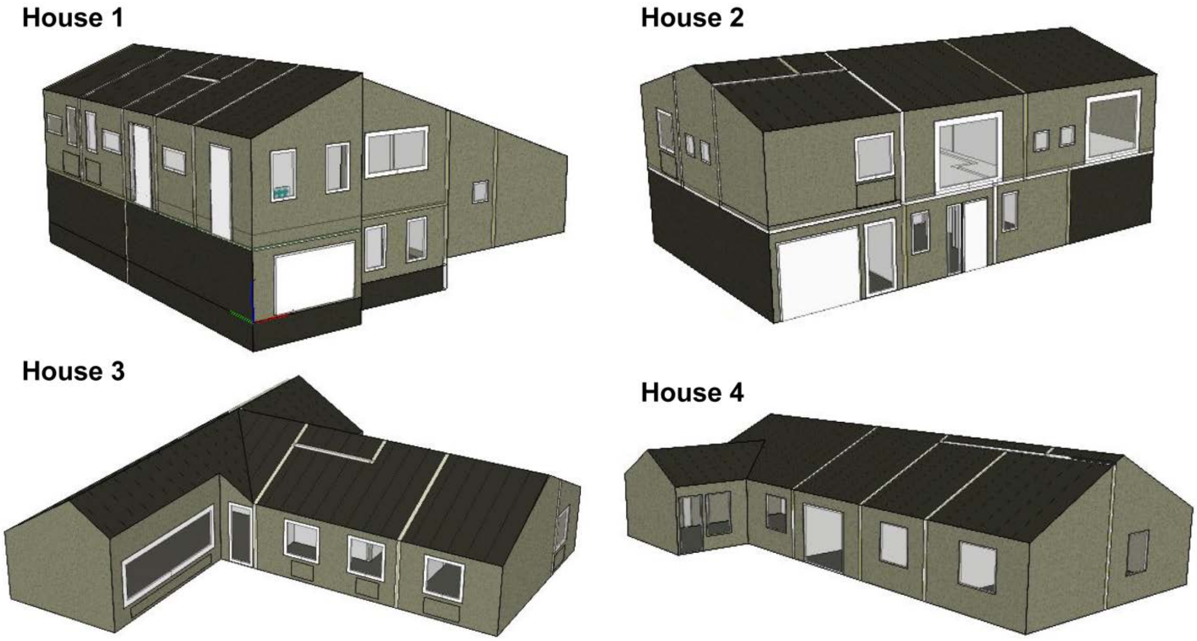

Fig. 2. Illustrations of the four case houses investigated in the study.

Table 1. Estimated U-values and description of constructions of the four houses.

Construction	House 1 (*W/m² K*)	House 2 (*W/m² K*)	House 3 (*W/m² K*)	House 4 (*W/m² K*)
External walls – Brick, insulation, and light weight concrete	U = 0.22	U = 0.32	U = 0.32	U = 0.32
Basement floor – Concrete, insulation, and Leca insulation	U = 0.26	U = 0.69	U = 0.28	U = 0.29
Roof – 200 mm insulation	U = 0.2	U = 0.2	U = 0.2	U = 0.2
Windows	U = 1.86	U = 2.68	U = 1.86	U = 2.68

All four single-family houses are supplied by DH and equipped with the original hydraulic radiator heating systems. DH is connected to the houses through a direct connection. The houses are equipped with different solutions for preparation of DHW by use of additional electric energy – these are described by Xiaochen in [15] and will not be described further here. The substation is not equipped with mixing valves or weather compensation control, as the overall DH supply temperature is controlled at plant level, according to outdoor temperature, as illustrated in Fig. 3(a). The radiators in the houses are standard Type 11 and Type 22 radiators, except from a few convector type radiators where windows begin at floor height. All radiators are equipped with individual thermostatic valves. The bathrooms in the houses are equipped with hydraulic floor heating systems, which are embedded in the concrete floors. The floor heating circuits are controlled by thermostatic valves. No central temperature control is installed in the houses.

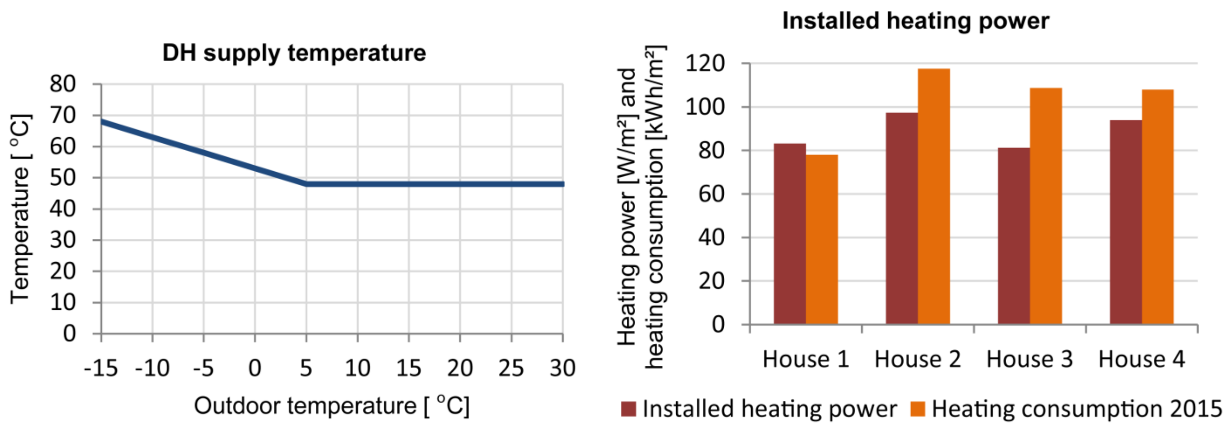

Fig. 3. (a) Variation of supply temperature from the district heating plant according to outdoor temperature; (b) Measured heating consumption in 2015 and installed heating power at the temperature set 70 °C/40 °C in the four case houses.

3. Method

3.1. Dynamic building simulations

The houses were modelled in the dynamic building simulation tool IDA ICE in order to calculate the expected heating system return temperature, and evaluate the thermal comfort in the houses, when the DH supply temperature is lowered. IDA ICE is a commercially available node based multi-zone simulation tool. The tool has been validated in accordance with standard DS/EN 15265, which describes the accuracy of dynamic simulations of energy performance in buildings [16,17]. The program calculates the heat balance of the buildings for every hour of the year, and has a high level of detail, that includes amongst others thermal inertia of building materials, and air flow between building zones. The program does not take into account temperature gradients in the rooms, and therefore air is assumed to be perfectly mixed in all rooms. This is not assumed to be a problem as none of the rooms in the investigated houses are too high.

The input data required to perform a specified simulation in IDA ICE includes for example air change rates and occupant schedules. This information was defined based on standard values for Danish single-family houses as given by [13,18]. All houses are naturally ventilated and it was assumed that the ventilation rate is 0.3 l/s per m2 which is the standard minimum required air change rate in Danish single-family houses [19]. Internal heat gains from presence of occupants and use of equipment was modelled by weekly schedules that were constructed for each house according to the number of occupants. The total average internal heat gains in the houses according to the schedules were 4.11-5.08 W per m2 living area, which corresponds well to the Danish standard value of 5 W/m2 [18]. Energy consumption for domestic hot water was not included in the models and the simulation models were run with weather data for the Design Reference Year of Copenhagen 2001-2010. Measured heat consumption is therefore adjusted according to the number of degree days, before it is compared the calculated heat consumption.

The simulation models were used to calculate the average monthly heating system return temperatures. The program calculates the heating system temperatures based on the mass flows and return temperatures from the individual radiators in the houses. The radiator temperatures and mass flows are calculated for every hour of the year according to the indoor temperature set-point and heat loss in the given rooms. The radiators are therefore included in the models with the actual location, dimensions, and design heating power. Radiator types and dimensions were noted at a visit to the house, and used to find the design heating power of the radiators, by use of a tool that was acquired from the Danish Technological Institute through personal communication. The tool makes it possible to estimate the heating power of a given existing radiator based on empirical data. The average heating power installed in each house is summarized in Fig. 3(b). The figure also shows the total measured heat consumption in each of the houses during 2015. Each radiator is controlled by a P-control thermostatic radiator valve with a P-band of 2 °C that controls the water mass flow through the radiator and aims to maintain the indoor temperature set-point. The floor heating was assumed to be controlled by similar thermostatic valves, and according to a constant flow, and a maximum coil temperature difference of 5 °C. The heating pipes were assumed to be located at a depth of 0.04m in the concrete slab with tile flooring. The heating system supply temperature was defined according to the weather compensated DH supply temperature. Due to the heat losses in the DH pipes, the supply temperature reaching the houses was assumed to be 6 °C lower than the temperature illustrated in Fig. 3(a), which was found to correspond well to the measured temperatures.

The thermal comfort in the houses was evaluated through an analysis of the calculated indoor air temperatures in each room of the houses. This was done by counting the number of hours during the year, where the indoor air temperatures, according to the simulations, were below the temperature set-point. For this analysis the occupants were expected to maintain an indoor temperature of 20 °C in living areas and 18 °C in the basement. Even so, it should be kept in mind that actual indoor temperatures usually vary greatly due to differences in occupant preferences [20, 21].

3.2. Heating system measurements

The actual space heating temperatures in the houses were evaluated for the period from July 2015 to March 2016, where the houses were supplied by ULTDH. The measurements were conducted by use of energy meters that have an accuracy of approximately ±0.5 %, according to the manufacturer. The meters were used to measure temperatures, volume, and mass flow of the DH water for the overall district heating connections, and for the preparation of domestic hot water, as illustrated in Fig. 4.

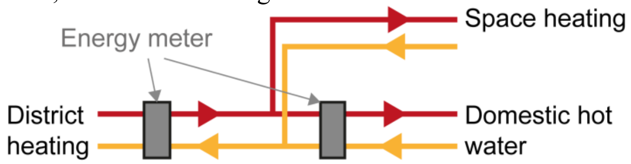

Fig. 4. Illustration of the measurement setup.

The average monthly space heating temperatures were calculated based on the measurements as follows. First the volume of DH that was used for space heating purposes (VSH) was calculated from the total volume of the DH water (VDH) and the volume of DH used for DHW (VDHW) as seen in Equation (1).

$$V_{SH} = V_{DH} - V_{DHW} \tag{1}$$

Afterwards the return temperature from the space heating (Tret,SH) was calculated based on the volumes and the return temperature from the DHW (Tret,DHW) and the DH in total (Tret,DH). This was done according to Equation (2).

$$T_{ret,SH} = \frac{V_{DH} \cdot T_{ret,DH} - V_{DHW} \cdot T_{ret,DHW}}{V_{SH}} \tag{2}$$

The return temperatures were generally based on volume weighted averages. However for some months the DH return temperatures were calculated as an average of the daily volume weighted return temperature. This is not expected to cause significant inaccuracies, as there were rarely any large variations in the day to day measurements. Due to logger problems, it was not possible to calculate the space heating return temperature in house 4, until December. The space heating return temperature for this house, in the months before then, was therefore assumed to be equal to the DH return temperature. This was found to be reasonable, as the study generally found that the space heating return temperature and the DH return temperature were often merely the same.

4. Results

Table 2 shows a comparison of the degree day adjusted space heating consumption that was measured in the houses and the heating consumption that was calculated by use of the simulation models. It can be seen from the table that the measured and calculated heating consumption differs by up to 13.6 %. The deviation could be partly explained by a difference between the indoor temperatures assumed in the simulation, and the actual indoor temperatures in the house. Some of the houses are additionally heated by a fire stove, which could furthermore cause a deviation between the measured and the calculated heating consumption. Alternatively, the numbers could indicate that the simulation model for House 3 tends to overestimate the heating demand, while the model for House 4 underestimates it.

Table 2. Deviation between simulated and measured space heating consumption (July-March).

House	Calculated (MWh)	Measured (MWh)	Deviation (%)
1	11.64	11.72	0.6
2	13.16	13.95	5.7
3	10.39	9.52	-9.1
4	10.82	12.53	13.6

4.1. Supply and return temperatures

The average monthly space heating temperatures in the houses, according to the simulations and the measurements, are compared for all of the four houses in Fig. 5. The figure also holds the average monthly outdoor temperatures for the measurement period and the DRY weather file. The average outdoor temperatures in the winter of 2015-2016 were found to be somewhat higher than the temperatures in the weather file.

The results show that the space heating in the houses was generally delivered by supply and return temperatures around 40 °C/30 °C or 45 °C/35°C. The measured space heating return temperature was found to be below 30 °C in a few months of the year in houses 1,3 and 4. Especially House 3 was seen to have a low space heating return temperature. As seen from Fig. 3(b) this does not seem to be explained by significantly lower heat consumption or higher installed heating power.

The simulated and measured space heating return temperatures were found to correspond well for most of the houses. This indicates that the technical potential to lower the heating system temperatures was met in most of the houses. The correlation between measured and simulated temperatures was striking especially in House 3, despite of the difference between the simulated and measured heating consumption. In House 2, on the other hand, it was found that there was a deviation between the simulated and measured return temperature of up to 10 °C. This could be due to the fact that the occupants in this house prefer higher indoor temperatures than the assumed 20 °C, which could be indicated by the high measured heat consumption seen in Fig. 3(b) and Table 2. Nevertheless, the simulation results could also indicate, that there is a potential to obtain significantly lower space heating return temperatures in house 2, if the heating system control is optimized.

4.2. Thermal comfort

In most of the rooms in the single-family houses, it was found that the indoor air temperature never dropped below the set-points of 20 °C and 18 °C. However the simulation results indicated that it was difficult to maintain the thermal comfort temperature in the restrooms in Houses 2-4, where the indoor air temperature was found to be around 19 °C for a large part of the year. These rooms are heated solely by floor heating, which is generally operated with a low supply temperature, and therefore the thermal comfort in these rooms should not be affected by the changes in the DH temperatures. Rather the results may suggest that the heating power of the floor was under-estimated, due to uncertainties on the construction and operation of the floor heating. Fig. 6 shows a visualization of the number of hours during the year, where the indoor air temperature drops below the indoor temperature set-point.

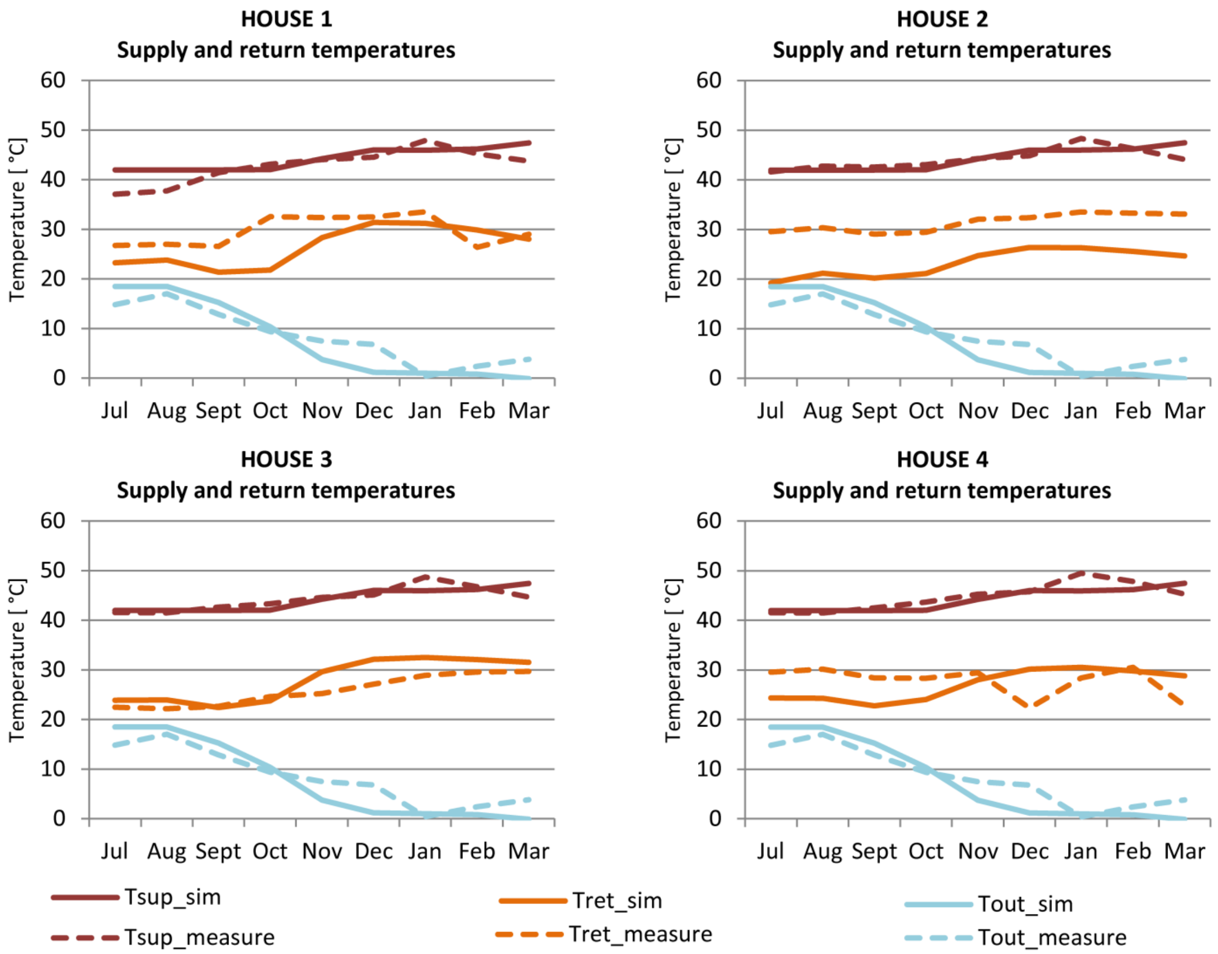

Fig. 5. Simulated and measured space heating temperatures in the four houses.

4.3. Uncertainties

There were found to be two main uncertainties in this study: the construction of the floor heating systems and the indoor temperature set-points. The impact of these uncertainties was evaluated through new simulations of the houses, where two changes were made in the models. Firstly, the floor heating was modelled as plain electric heating. Thereby the heating power of the floor was not affected by the floor construction, and the return temperature from the floor heating did not affect the overall space heating return temperature. Secondly, the indoor temperature was set to approximately 21.5 °C in all living areas. According to a recent study of typical British homes, an indoor temperature of 20 °C or lower, could be a reasonable estimate of average living room temperature, but it is only an average temperature, and actual indoor temperature in many living rooms is higher [21]. Likewise our own studies have showed that indoor temperatures of 21-22 °C are not uncommon in living and dining rooms of Danish single-family houses [22].

Despite of the simplification of the floor heating in the restrooms, the test simulations showed, similar to the first simulations, that it can be difficult to meet the thermal comfort criteria in the bathrooms of House 3 and 4. One explanation could be that the heating power of the floor heating was under-estimated. This seems more likely than the explanation, that the rooms are lacking heating power, as the occupants do not complaint about poor comfort, and floor heating capacity should not be affected by the lowered temperatures. Generally, the results of the test simulations showed, that indoor temperatures of approximately 21.5 °C could be maintained in all living areas of the houses. Even when the indoor temperature was increased, the return temperature from the radiators only increased slightly. In houses 1-3, the radiator return temperature was found to increase by 1-2 °C in the winter months, while in house 4 it was increased by approximately 4.5 °C. The increased return temperature in house 4 was mainly found to occur due to high return temperatures from the radiators in the entrance and the restroom, where indoor temperatures were also set at 21.5 °C. The results of the test simulations suggest that the findings of the study are generally robust to uncertainties on occupant preferences and indoor temperature set-points. This conclusion is further underlined by the measurements and the fact that none of the customers' complained about problems with the indoor temperature during the test period with ULTDH.

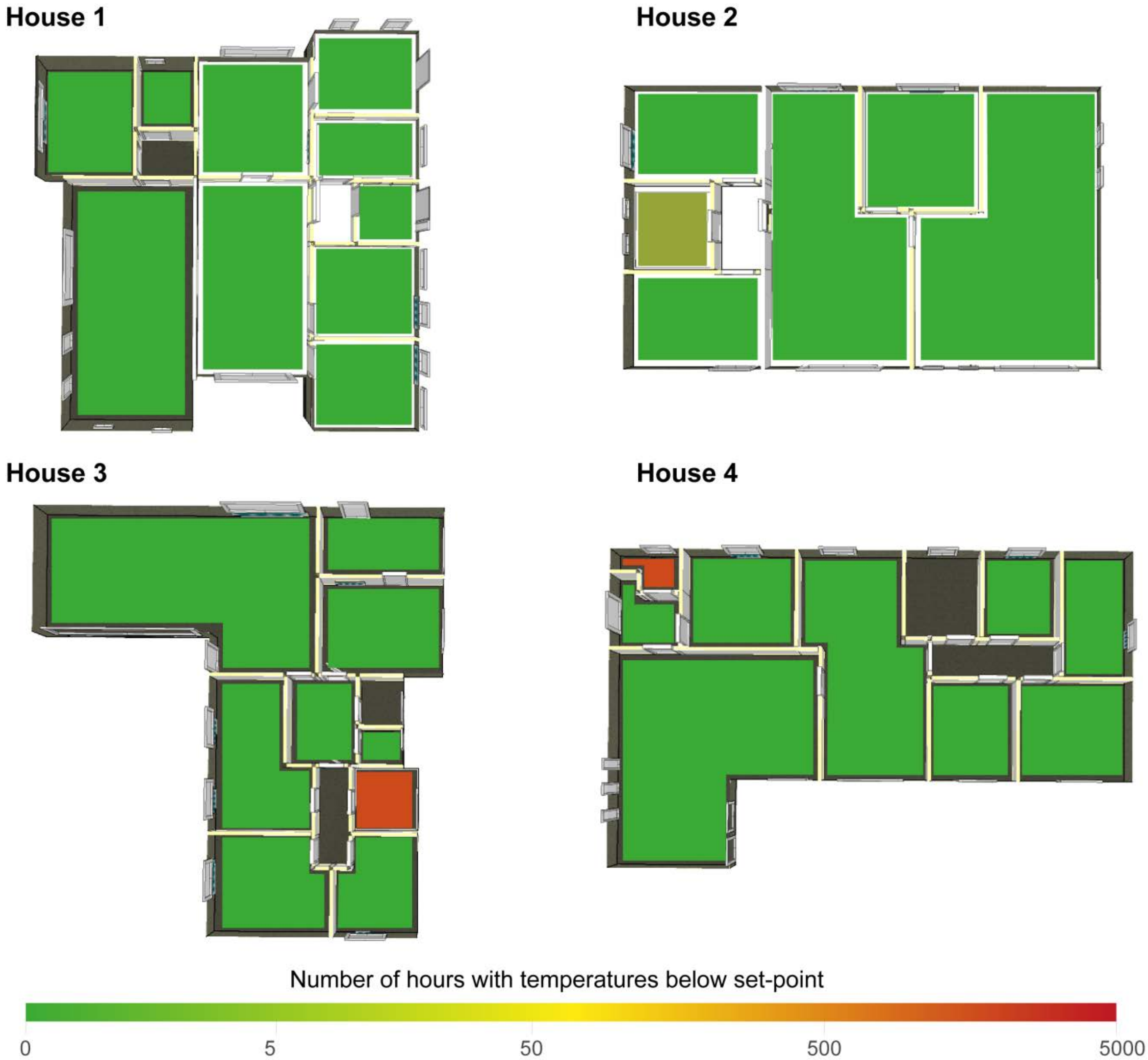

Fig. 6. Visualization of the simulated thermal comfort in the houses

5. Conclusions

The results of this study showed that there is a great potential to heat existing single-family houses with hydraulic radiator systems, with ultra-low-temperature district heating. Simulation results indicated that even when the heating system supply temperature was lowered to 45 °C for most of the year, this did not jeopardize the thermal comfort of the occupants living in the houses. This was further underlined by the fact that no consumers' complained about poor thermal comfort during a test with lowered return temperatures in a period from 2015-2016.

Both results from a simulation of the heating system operation in four single-family houses, and measurements from the test operation with ultra-low-temperature district heating, showed that there is a large potential to lower the district heating temperatures in existing single-family houses. Average supply and return temperatures for space heating in the houses were found to be 44 °C and 31 °C respectively.

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